

MODULAR REFORMER WITH ENHANCED HEAT RECUPERATION

BACKGROUND

Cross-Reference to Related Applications

5 This application claims priority and benefit of U.S. Provisional Patent Application No. 60/551,452, filed March 9, 2004, herein incorporated by reference in its entirety.

Field

10 The present invention relates generally to chemical reformers and more particularly to thermally driven reformers used for the production of hydrogen, and more particularly to hydrogen reformers fuelled by gaseous or liquid hydrocarbon fuels, organic fuels, and hydrogen containing compounds such as ammonia. The hydrogen generated in the reformer can be purified or not and can be used for integration with fuel cell systems and/or hydrogen refueling stations.

Background Art

15 The thermal reforming method uses a thermal energy reactor to decompose fuel into hydrogen and other compounds. This decomposition is typically done in the presence of a catalyst but does not have to include catalysts. Hydrocarbon and organic fuels are typically decomposed in the presence of water and typically produce hydrogen, carbon dioxide, and carbon monoxide. Thermal cracking-type reformers
20 typically do not use water, and therefore, also produce solid carbon or nitrogen if ammonia is utilized as the fuel. The most typical thermal reformer used in industry is a steam reformer type reactor, but other reactors can also include oxygen, which are known as auto thermal reformers and partial oxidation reformers. These reformers can be integrated with pre and post reactors such as steam generation and water gas
25 shift reactors to create a fuel processing system.

In applications such as fuel cell systems and hydrogen refueling stations the efficiency of the hydrogen generation equipment can be critical to overall system economics when the energy value of hydrogen is converted into electricity. Similarly, reformers that are more compact with smaller foot prints and packaging flexibility are
5 needed to reduce equipment cost and enhance the cost effectiveness of integrated system. In addition, fuel cell and hydrogen refueling applications are not homogeneous in capacity, some applications requiring only a few kilowatts and some requiring several hundred kilowatts. As a result, a reformer engineered for 25 kW applications must be completely re-engineered for a 2kW or a 100 kW application.
10 What the market needs are reformers with greater efficiency, enhanced compactness, and improved modularity.

SUMMARY

In an aspect, a thermal reformer system has a planar geometry, heat exchanger type, modular reformer with integrated thermal energy recuperation.

15 In an aspect, a thermal reformer includes sheet metal construction designed such that process gases flow from inlet manifolds, located at outer edges, inward toward a higher temperature primary reactor zone located centrally at a core and such that reactor products flow outwardly toward outlet manifolds also located on the outer edges and such that the inward flowing gases and the outward flowing gases are in
20 thermal contact to enhance energy recuperation within the planar (sheet metal) construction of the thermal reformer.

In an aspect, a thermal reformer has (sheet metal) planar geometry, heat exchanger type, modular construction designed such that 1) reformate process gases flow from manifolds located on the outer edges, inward toward a primary reactor
25 zone; 2) combustor inlet gases enter manifolds in the center of the structure and flow outward toward the reactor zone; 3) reformate and combustion products flow outwardly toward manifolds also located on the outer edges; 4) primary reactor zone(s) is located between the outside manifolds and the inside manifold(s); 5) inward flowing reformate process gases and the outward flowing reformate and combustion

product gases are in thermal contact to enhance energy recuperation within the planar (sheet metal) structure of the thermal reformer.

5 In an aspect, a planar (sheet metal) geometry, modular thermal reformer includes modular reformer elements each substantially consisting of all process reactors and heat exchangers such that when stacked one on the other form a thermal reformer package/assembly with variable capacity based on the number of modular reformer elements included in the stack.

10 In an aspect, a thermal reformer system comprises a planar assembly including a reformer zone, a combustion zone, an inlet reformat process fluid manifold, an outlet reformat process fluid manifold, an inlet combustion fluid manifold, an outlet combustion fluid manifold, an inlet reformat process fluid flow passage connecting the inlet reformat process fluid manifold and the reformer zone, an outlet reformat process fluid flow passage connecting the reformer zone and the outlet reformat process fluid manifold, an inlet combustion fluid flow passage connecting the inlet combustion fluid manifold and the combustion zone, and an outlet combustion fluid flow passage connecting the combustion zone and the outlet combustion fluid manifold. The reformer zone and combustion zone are in thermal contact to promote transfer of combustion heat into the reformer zone to drive a reaction in the reformer zone. An exemplary reaction is a reformation reaction that produces at least hydrogen as a product.

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In some exemplary implementations, the primary reactor zone consists of the reformer zone and the combustion zone, centrally located within the assembly. In still other configurations, a plurality of planar assemblies can be provided and stacked one atop the other to provide a modular reformer assembly of one or more individual assemblies.

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In an aspect, the inlet reformat process fluid flow passage is provided and configured to be in thermal contact with the outlet reformat process flow passage

and/or the outlet combustion fluid flow passage to promote transfer of heat from outlet fluid(s) to inlet fluid(s).

In some exemplary implementations, the inlet reformat process fluid flow passage is located circumferentially within the assembly. In still another aspect, the inlet combustion fluid flow manifold is divided into an inlet combustion air manifold and an inlet combustion fuel manifold. In one aspect of the disclosure, the inlet combustion fluid flow passage is provided such that it is divided into an inlet combustion air passage and an inlet combustion fuel passage. In still another particular aspect of one embodiment, the inlet reformat process fluid manifold is divided into an inlet water/steam manifold and inlet fuel/water/steam manifold. In another aspect, the inlet reformat process fluid flow passage can be provided dividing into an inlet water/steam passage and an inlet fuel/water/steam manifold. The inlet water/steam passage and the inlet fuel water/steam manifold can also be provided in a configuration such that they are connected prior to entering the reformer zone.

In some exemplary implementations, the thermal reformer system can include an outlet reformat process fluid flow passage divided into any one of a pre-shift flow passage, a shift reactor, and a post shift flow passage. In some examples, the pre-shift flow passage or the post shift flow passage are single or multiple passages that define a conduit connecting appropriate manifolds to a primary reactor zone. In some embodiments, the pre-shift flow passage and said post shift flow passage are provided in a counter-current configuration, respectively, such that flow therein flows in opposing directions. In other examples, the pre-shift flow passage and post shift flow passage are both provided in a configuration such that flows therein flow concordantly in same general direction within said planar assembly.

In some exemplary implementations, the thermal reformer system includes one or more of inlet reformat process fluid manifold, an outlet reformat process fluid manifold, an inlet combustion fluid manifold, an outlet combustion fluid manifold located externally to the planar assembly.

In some implementations, the assembly is constructed of sheet metal components. In some implementations, at least one of the an inlet reformat process fluid flow passage, outlet reformat process fluid flow passage, inlet combustion fluid flow passage, reformer zone and combustion zone are created by pressed sheet metal components and/or etched sheet metal components.

BRIEF DESCRIPTION OF DRAWINGS

The invention will be better understood by reference to the accompanying drawings, which represent exemplary implementations in accordance with the present disclosure:

10 Figure 1A illustrates a cross sectional view of an exemplary implementation of a modular reformer assembly having multiple modular reformer elements;

Figure 1B illustrates a cross sectional view of individual components of a modular reformer element according to one embodiment;

15 Figure 1C illustrates a cross sectional view of inlet and outlet flow passages of a portion of Figure 1B, according to one embodiment;

Figure 2A is a top view illustrating an inlet side of a reformat inlet component of a reformation side of a modular reformer element;

Figure 2B is a top view illustrating an outlet side of a reformat outlet component of a reformation side of a modular reformer element;

20 Figure 2C is a top view illustrating the inlet side of a combustion inlet component of a combustion side of a modular reformer element;

Figure 2D is a top view illustrating the outlet side of a combustion outlet component of a combustion side of a modular reformer element;

25 Figure 3 is an illustration of an exemplary implementation in which the combustion side of a modular reformer element is constructed from three sheets, a

combustion fuel inlet sheet, a combustion air inlet sheet, and a combustion exhaust sheet;

Figure 4 is an illustration of an exemplary implementation, in which an outlet reformat fluid flow passage is modified to include a shift reactor section;

5 DETAILED DESCRIPTION

Particular exemplary implementations are described below in considerable detail for the purpose of illustrating various teachings, principles and methods of operation. However, various modifications including, but not limited to scale, orientation and composition may be made and the scope of the disclosure is not
10 limited to exemplary implementations described herein.

Figure 1A illustrates a modular reformer assembly (1) constructed from multiple modular reformer elements (2) which have been stacked together. Also shown is the addition of a top end plate (3) and the bottom end plate (4) between which the planar modular reformer elements are assembled. The materials of
15 construction can be any appropriate metal or ceramic material based on the temperature and pressures associated with the temperatures at which specific fuels are reformed. With hydrocarbon fuels such as but not limited to natural gas, gasoline, kerosene, diesels, propane, etc. the reforming and combustion reactions will be maintained at higher temperatures from 650C to over 900C, depending on the specific
20 composition of the fuel. Alcohols and other oxygenated fuels can be reformed at lower temperatures from 250C to 650C. For metal based thermal reformers stainless steels are most appropriate, including but not limited to austenitic stainless steels, 300-series, 400-series, and the superalloy grades such as the high temperature Inconel 600-series and Hastelloy-series. Similarly, ceramic materials such as alumina,
25 alumina doped with magnesium oxide, zirconia, yttria-stabilized zirconia, ceria, silicon nitride, silicon carbides, etc can be used in any embodiment of this thermal reformer, which provide the temperature and chemical compatibility required for a high temperatures and stability in the hydrogen rich environment.

Figures 1B and 1C illustrate the modular reformer element (2) in greater detail. In this exemplary implementations, the modular reformer element (2) is constructed from four components. A first component is the reformat inlet component (10) which supports an inlet reformat process fluid flow passages (11).
5 The second is the reformat outlet component (20) which supports the outlet reformat process fluid flow passages (21). The third is the combustion inlet component (30) which supports the inlet combustion fluid flow passages (31). The fourth is the combustion outlet component (40) which supports the outlet combustion fluid flow passages (41). In one embodiment, each component the fluid flow
10 passages (11, 21, 31, and 41) are formed by chemical etching to a depth greater than 50% and preferably to 55% to 65%, but depths as high as 90% can be used depending on the initial thickness of the component. Other methods for forming the fluid flow passages (11, 21, 31, and 41) in their respective components can include, but are not limited to stamping, pressing and laser etching or other known etching technique. In
15 some of these techniques the individual components (10, 20, 30, and 40) can be composed of two sheets: one sheet that has been cut completely through the thickness forming the volume for the fluid flow passages and reactions sections, while the other is not cut in the areas related to the fluid flow passages such that when the two sheets are stacked on to each other and bonded the general configuration is similar to the
20 individual components (10, 20, 30, and 40) shown. The individual components can also be made of several sheets stacked and bonded together. For example the region of the component with fluid flow fields passages may be constructed from several sheets while the non-cut region can be a single sheet to provide appropriate isolation between the various fluid flow passages. The thickness of the individual sheets or
25 layers (10, 20, 30, and 40) can be the same or different. Typically, the individual components (10, 20, 30, and 40) will be in the range of 0.1 to 50 mm thickness, and preferably in the range of 1 to 40 mm thickness, and most preferably in the range of 1 to 4 mm thickness.

Figures 1B and 1C illustrate a reformation cavity (5) and the combustion
30 cavity (6). The reformation cavity (5) is created by completely etching away a

reformation zone of the reformat inlet component (10) and approximately 60% etching of the reformation zone of the reformat outlet component (20). Similarly, the combustion cavity (6) is created by completely etching away the combustion zone of the combustion inlet component (30) and approximately 50% etching of the combustion zone of the combustion outlet component (40). Chemical etching is one preferred fabrication approach but other techniques are also applicable such as but not limited to compression forming, powder metal forming, casting, etc. The components can be constructed from metal or ceramic materials.

It is also contemplated that inlet reformat process fluid flow passages (11) and outlet reformat process fluid flow passages (21), can be provided on opposite sides of reformat inlet component (10) by utilizing appropriately shallow etching of passages and arrangements/stacking of components to maintain appropriate sealing of the various flow passages.

Figures 2A and 2B illustrate a top view of the two components that create the reformation side of the modular reformer element. Figure 2A illustrates a reformat inlet component (10) and Figure 2b illustrates a reformat outlet component (20). Reformat inlet process fluids such as a fuel / water / steam mixture enter the assembly through inlet reformat process fluid manifold (15) and flows along the half etched inlet reformat process fluid flow passages (11) until it enters the inlet flow distribution region (12) and into the reformation cavity (5). The reformation cavity (5) is constructed by the fully etched region (13) of the reformat inlet component (10) and the partially etched region (23) of the reformat outlet component (20). Catalyst inserts can be used to provide high surface area structures in the reformation cavity (5). The reformat fluids exit the reformation cavity (5) and enter the outlet distribution region (22) of the outlet reformat process fluid flow passage (21). This fluid flows along the outlet reformat process fluid flow passage (21) and enters a reformat outlet manifold (26) which is in fluid connection with manifold (16) of the reformat inlet component (10). Also shown are manifold ports (17) and (27) through which combustion inlet fluids flow and manifold ports (18) and (28) through which combustion outlet fluids flow.

Figures 2C and 2D also illustrate top views of two components that form the combustion side of the modular reformer element (2). Figure 2C illustrates the combustion inlet component (30) and Figure 2D illustrates the combustion outlet component (40). Combustion inlet process fluids such as air / off-gas / fuel mixture enter the assembly through combustion fluid inlet manifold (37) and flows along the half etched inlet combustion fluid flow passages (31) until it enters the combustion fluid flow distribution region (32) and into the combustion cavity (6). The combustion cavity (6) is constructed by the fully etched region (33) of the combustion inlet component (30) and the partially etched region (43) of the outlet combustion component (40). Catalyst (not illustrated) inserts can be used to provide high surface area structures in the combustion zone. The combustion exhaust fluid exits the combustion cavity (6) and enters the outlet distribution region (42) of the outlet combustion fluid flow passage (41). This fluid flows along the outlet combustion fluid flow passage (41) and enters the combustion outlet manifold (48) which is in fluid connection with manifold (38) of the reformate inlet component (30). Also shown are manifold ports (35) and (45) through which reformate inlet fluids flow and manifold ports (36) and (46) through which reformate outlet fluids flow.

This implementation provides one example of the aspect disclosed herein. The planar modular reformer with integrated thermal energy recuperation is constructed using four sheet metal plate components each with chemically etched surfaces and integrated manifolds. An aspect configuration can be achieved using pressed plate components or cast components. The materials could also be ceramic or metal ceramic composites similar to those disclosed above. A feature disclosed herein integrates the thermal recuperative heat exchange area created by fluid passages (11, 21, 31, and 41) within the planar assembly such that the outlet fluids transfer most of their thermal energy into the inlet fluids and such that much of this recuperation occurs along the outer edges of the assembly to minimize heat loss and insulation requirements due to the efficiency of counter current exchange of thermal energy between the outlet fluids (having increased thermal energy as they emanate from the centrally located respective combustion and reformation cavities) and

incoming inlet fluids (which contain relatively lower thermal energy as they are fed into their respective channels and towards the core) on their way to their respective combustion and reformation cavities. Shown in Figure 2A and 2B, are incoming process fluids such as a fuel / water / steam mixture enter the assembly through inlet reformat process fluid manifold (15) and flow along the half etched inlet reformat process fluid flow passages (11) in a counter-clockwise fashion until it enters the inlet flow distribution region (12) and into the reformation cavity (5) and then after reformation has taken place, reformat fluids exit the reformation cavity (5) and enter the outlet distribution region (22) of the outlet reformat process fluid flow passage (21) which flows along the outlet reformat process fluid flow passage (21) in a clockwise fashion oppositely of the flow of incoming process fluids. This counter current outlet and inlet fluid flow maximizes the overall process efficiency by efficient heat transfer, minimizing the amount of energy required in the combustion section and insulation requirements. A similar configuration is likewise provided in the combustion portion of the planar modular reformer (see Figure 2C and 2D).

Another aspect shown includes the integrated manifolds that support the stacking of the modular reformer elements (2), one on top of the other and providing capacity flexibility without extensive re-engineering. If each element assembly is designed with sufficient catalyst volume for 1kWe hydrogen, then a stack of five modular reformer elements (2), as illustrated in Figure 1a, would provide sufficient hydrogen for a 5kWe application. Similarly, twenty-five elements could be used for a small commercial application requiring 25kWe of energy. The fluid flow manifolds are sized for the maximum number of elements in a stack, and a system of greater capacity can be achieved by using external manifolds between individual stacks. The planar configuration also supports maximizing the direct heat transfer area between the reformer and the combustion zones and fluid flow passages (e.g. transfer of heat energy from outlet fluid flow passages to inlet fluid flow passages). This further supports higher efficiency and allows lower temperatures within the combustion zone.

Figure 3 illustrates a configuration that minimizes combustion temperatures by dividing the combustion gas inlet manifold and passage into two parallel passages and

using a distributed combustion configuration. For example, the combustion side of the modular reformer element (2) can be designed as three separate layers, one for the combustion fuel inlet (50), one for combustion air inlet (60) and one for combustion exhaust outlet (70). The combustion fuel enters through port (51) flows along passage (52) and enters fuel distribution zone (53). The fuel flows through distribution holes (54) and into the combustion zone (64). The combustion air enters through port (61) flows along passage (62) and enters combustion zone (64) where it reacts with the fuel flowing through holes (54). The heat generated is transferred into the reformer zone (not illustrated) and the distributed combustion helps maintain uniform temperatures within both the combustion zone (64) and the reformer zone (other side of modular reformer element (2)). The combustion exhaust fluids exit the combustion zone and flow into passage (72) transferring heat into the inlet fluids in passages 52 and 62 of combustion fuel inlet (50) and combustion air inlet (60), respectively. Heat can also be transferred into inlet process fluids flowing through the reformat component (not illustrated). The pattern of the distributed combustion holes (54) can be tailored to create uniform and controlled temperature distributions within the combustion zone.

Figure 4 illustrates an implementation that improves the hardware (100) by separating the reformat outlet fluid passage into an outlet reformat passage (121), a shift reactor passage (107), and a shift outlet passage (109). This implementation illustrates a reformer subassembly (120) and combustion subassembly (140). The outlet side of the combustion subassembly (140) is visible illustrating combustion outlet manifold (147), the end of the outlet combustion passage (141), and the combustion zone (106). The outlet side of the reformer subassembly (120) is visible. The reformat gases flow from the reformer zone (105), into the outlet reformer passage (121) which circulates around the reformer zone (105) providing heat to the inlet reformer fluids contained within the subassembly (not illustrated). These gases then enter the shift reactor zone (107) which also circulates around the central zones and eventually exits (108) into the outlet reformer passage (109) and eventually outlet manifold (126). In this implementation the combustion inlet fluid flow passages (not

shown) is contained within the thickness of subassembly (140) and the combustion outlet fluid flow passage (141) terminating at manifold (147) do not flow through the closed region (109) of subassembly (140). This region can therefore be opened up to the be in fluid communication with the shift reactor zone (107) to increase the volume of the shift reactor zone (107). The water gas shift function of the fuel processor are integrated into the modular assembly.

Some reformer implementations herein disclosed are planar in geometry with integrated manifolds to support stacking of multiple modular reformer elements (2) which provides flexibility in reformer capacity without major engineering redesigns. The modular reformer elements are designed such that process fluids typically flow from the outer edges of the individual modular reformer elements inward toward the higher temperature combustion and reforming zones, while the exhaust and outlet fluids typically flow outward from the higher temperature zones. This configuration promotes thermal recuperation between the inlet and outlet process and combustion fluids which in turn increases process efficiency and reduces thermal energy loss from the external surfaces.

A thermal reformer system may include a planar assembly including a reformer zone, a combustion zone, an inlet reformat process fluid manifold, an outlet reformat process fluid manifold, an inlet combustion fluid manifold, an outlet combustion fluid manifold, an inlet reformat process fluid flow passage connecting the inlet manifold and the reformer zone, an outlet reformat process fluid flow passage connecting the reformer zone and the outlet reformat process fluid manifold, an inlet combustion fluid flow passage connecting the inlet combustion fluid manifold and the combustion zone, and an outlet combustion fluid flow passage connecting the combustion zone and the outlet combustion fluid manifold. The reformer zone and combustion zone may be in thermal contact to promote transfer of combustion heat into the reformer zone driving the reaction. A primary reactor zone may be present consisting of the reformer zone and the combustion zone which are centrally located within the assembly, and the planar assemblies can be stacked to create a modular reformer assembly of one or more individual assemblies.

In addition, the inlet reformat process fluid flow passage may be in thermal contact with the outlet reformat process flow passage and/or the outlet combustion fluid flow passage to promote transfer of heat from the outlet fluid(s) to said inlet fluid(s). Further, the inlet reformat process fluid flow passage may be located
5 circumferentially within the assembly to minimize circumferential temperature of the assembly.

The inlet combustion fluid flow manifold may be divided into a inlet combustion air manifold and an inlet combustion fuel manifold. The inlet combustion fluid flow passage may be divided into a inlet combustion air passage and an inlet
10 combustion fuel passage to minimize the likelihood of combustion prior to entering the combustion zone.

The inlet reformat process fluid manifold may be divided into a inlet water/steam manifold and an inlet fuel/water/steam manifold. The inlet reformat process fluid flow passage may divided into a inlet water/steam passage and an inlet
15 fuel/water/steam manifold, and the inlet water/steam passage and the inlet fuel water/steam manifold may be connected prior to entering the reformer zone.

The inlet water/steam passage may be used to dynamically control the temperature of the outlet reformat fluid along the outlet reformat fluid flow passage. The outlet reformat process fluid flow passage may be divided into pre-shift flow
20 passage, a shift reactor, and a post shift flow passage. The flow passages may be single or multiple passages connecting the manifolds and the primary reactor zone. The flow passages may have a clockwise or counter-clockwise direction or may have both a clockwise and counter-clockwise direction or any combination of directions within the planar assembly.

25 Further, the assembly may be constructed of sheet metal components and the flow passages and reactor zones may be created by pressed sheet metal components. The inlet flow passages and the outlet flow passages may be formed on opposite sides of the pressed sheet metal component. The flow passages and reactor zones may be

created by chemically etched sheet metal components. Similarly, the assembly may constructed of ceramic components and one or more of the manifolds may be external to the assembly.

- 5 While specific implementations have been illustrated and described herein for illustrative purposes, it is realized that modifications and changes will occur to those skilled in the art. It is therefore to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit and scope of the invention.